Atmospheric constraints on greenhouse gas budgets: Requirements on Modelling tools based on multiple observations

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CERES (Han Dolman, ...)
many CEIP Fluxtower PIs

EPFL Lausanne
May 4, 2008
Overview

• Motivation

• Model-data-fusion system

• Test data:
  - Tall tower measurements
  - CERES (CarboEurope regional Experiment)

• associated uncertainties, and possibilities for mitigation

• Closing remarks
Motivation

Scientific questions:

- Where and by which processes is anthropogenic $CO_2$ sequestered?
- What are the main feedback processes between carbon cycle and climate system?
- What is the carbon budget of a specific region (continent/country)?

Variable "Airborne fraction"
Estimating Regional Carbon Balances: Top-Down vs. Bottom-Up Approach
Estimating Regional Carbon Balances: Top-Down vs. Bottom-Up Approach

ZOTTO
(Zotino Tall Tower Observatory)
Central Siberia

Tall Towers

Atmospheric Observing System

FTIR: Fourier Transform Infrared

Satellites

OCO
~1 decade ago: only remote sites
Motivation

$\text{CO}_2$ in the continental atmospheric boundary layer:
- Variability on diurnal and synoptic scales
  $\Rightarrow$ Information on surface fluxes

[Gerbig et al., 2006]
Estimating Regional Carbon Balances: Top-Down vs. Bottom-Up Approach

Upscaling Prediction

1000 km Atmospheric Observing System

10 km Top Down Inversion

Future

Downscaling Verification

Process Studies

Ecosystem Flux Measurements

Atmospheric Transport
The challenge: we need ...

- Model-data fusion
  - merging Top-Down and Bottom-Up

- Test data, to assess models capability
  - Experiments with high density observations (space & time) -> CERES

- Falsifiable models
  - scalable from experiment scale to scale of interest
  - quantitative (error bars)
WRF-VPRM-STILT modeling system

Weather Research and Forecasting Model (WRF)

Vegetation Photosynthesis and Respiration Model (VPRM)

ECMWF meteorology

Modeled CO₂

Forested area

Eddy flux data measurements

“3D Gap-filling”

diagnostic biosphere model

Forward
VPRM Vegetation Photosynthesis and Respiration Model

[Pathmathevan et al., GBC 2008]

Optimization of parameters $\alpha$, $\beta$, $\lambda$, and $\text{PAR}_0$

$\text{NEE} = \text{GEE} + R \rightarrow = \alpha \cdot T + \beta$

ECMWF, NCEP, WRF or site measurements

MODIS surface reflectances 8 day, 500 m

SYNMAP land cover

[Jung et al., 2006]
2005 CEIP-EC data vs. VPRM (driven by site meteorology)

Spatial gradients:
- deciduous forests
- evergreen forests

Diurnal fluxes (June-July)
VPRM biospheric CO$_2$ fluxes

WRF-VPRM CO$_2$ (-366 ppm) at 150 m
VPRM biospheric CO$_2$ fluxes

WRF-VPRM column CO$_2$ (-366 ppm)
The WRF-VPRM-STILT modeling system includes the following components:

- **WRF-chem**: Weather Research and Forecasting Model
- **VPRM**: Vegetation Photosynthesis and Respiration Model
- **ECMWF meteorology**: Model for predicting weather
- **diagnostic biosphere model**: Integrates measured data with model simulations
- **Eddy flux data**: Measurements of CO₂ fluxes
- **Modeled CO₂**: Simulated CO₂ concentrations
- **Measured CO₂**: Observed CO₂ concentrations

The system also involves forward eddy flux data and uses diagnostic models to predict CO₂ concentrations.
Model-Data Comparison
Global model - Biscarrosse coastal station

Biscarrosse station, 16.05-15.06, 2005

- Observation
- LMDZ

stddev(diff) = 4.6649
bias = 0.11466
r2 = 0.29372
Model-Data Comparison
WRF-VPRM 2 km - Biscarrosse coastal station

Biscarrosse station, 16.05-15.06, 2005

Observation
WRF-VPRM

\[
\text{stdev(diff)} = 4.2615 \\
\text{bias} = 0.67438 \\
r^2 = 0.58669
\]
**WRF-VPRM vs. Aircraft data**

(CERES campaign)
Respired CO2 signal
10 ppm surface

$\text{CO}_2 = 10 \text{ppm} \quad 2005-05-26, 18^0\text{O}$

[Ahmadov et al., JGR 2007]
Mesoscale covariance of transport and CO2 fluxes “3D rectifier effect”
**WRF-VPRM-STILT** modeling system

- **Forward**
  - WRF-chem
    - Weather Research and Forecasting Model
  - VPRM
    - Vegetation Photosynthesis and Respiration Model
  - **modeled CO₂**
  - Eddy flux data

- **Inverse**
  - **measured CO₂**
  - Eddy flux data
  - **STILT**
    - Stochastic Time Inverted Lagrangian Transport Model
  - VPRM
    - diagnostic biosphere model
  - **regional scale CO₂ budgets**
  - **CO₂ at 300m agl (ppm)**

**Parameter Optimization**

- Eddy flux data
- Regional scale CO₂ budgets
- Parameter optimization scalars for R, GEE

**Weather Prediction**

- NEE-st [umol m⁻² s⁻¹]
- ECMWF meteorology
- Forward Inverse modeling system

**Regional Scale CO₂ Budgets**

- **01-Nov-05**
- **16-Nov-05**
- **01-Dec-05**

**WRF-chem**

- Weather Research and Forecasting Model

**VPRM**

- Vegetation Photosynthesis and Respiration Model

**STILT**

- Stochastic Time Inverted Lagrangian Transport Model

**CO₂ at 300m agl (ppm)**

- 01-Nov-05
- 16-Nov-05
- 01-Dec-05

**measurements**

- Forward WRF-VPRM-STILT modeling system
- Inverse measurements

**Forward Inverse Modeling System**

- CO₂ measured
- CO₂ modeled
- CO₂ budget
- Weather prediction model
- Regional scale CO₂ budgets

**Eddy Flux Data**

- Eddy flux data
- regional scale CO₂ budgets
- Parameter optimization scalars for R, GEE
STILT-VPRM

Stochastic Time Inverted Lagrangian Transport

- ECMWF winds + turbulence + convection
- Resolution: 1/12° x 1/8° (~10x10 km²)
- Biosphere: VPRM
- Emissions: IER (Hourly, 10 km) + EDGAR
- Lateral boundary condition: analyzed CO₂ fields (TM3 + Edgar + Takahashi + Biome-BGC)

IER + EDGAR CO2 fossil emissions

flux (micro-mole/m²/s)
STILT-VPRM

STILT-VPRM (regional)

CERES Dimo measurements
STILT @ Tall Tower

Bialystok tall tower

Bialystok tall tower footprints

Model: STILT-ECMWF

CO (measured)

CO (modelled, IER em.)
Aug 05 - Oct 06 Bialystok 300 m

Correlation coefficients model vs. measurement

Daytime only (13:30-16:30 GMT)

STILT-VPRM

TM3 analyzed fields

---2005------> <----------2006----------
8 tall towers (> 100 m) in Europe instrumented with continuous profile measurements

Optimize VPRM using STILT

=> Regional scale hourls fluxes at 10 km resolution
## Uncertainties involved (continental stations)

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- winds uncertain + spatial flux variability = mixing ratios uncertain
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- winds uncertain + spatial flux variability = mixing ratios uncertain
- comparison of radiosonde derived $z_i$ with ECMWF-fields derived $z_i$
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**Uncertainties involved (continental stations)**

- Mixing height uncertain = mixing ratios uncertain
- Comparison of radiosonde derived $z_i$ with ECMWF-fields derived $z_i$
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Spatial statistics of multiple profile measurements (COBRA experiments)
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pseudo data experiment, varying a-priori covariance length scale
“Eyesight of the atmosphere”
Reduction in flux uncertainty, spatially resolved, as function of a-priori covariance length scale

larger a priori covariance scales
⇒
larger scale „information“

⇒
Need good knowledge about prior uncertainty + covariance!

[Gerbig et al., ACP 2006]
## Uncertainties involved (continental stations)

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<tr>
<td>Measurement</td>
<td>Precision, accuracy</td>
<td>0.1 ppm (targeted)</td>
<td>WMO</td>
</tr>
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Mitigation?

Modifying some measurement strategies ...
PBL mixing problem

• Add a device to monitor mixed layer height
  - e.g. Ceilometer (operational at many airports and weather stations, globally ~5000)
    • Cheap LIDAR
    • Continuous observation of cloud base, but also vertical profile of backscatter up to 7.5 km possible
Regular vertical profiles: Aircraft

IAGOS (Integration of routine Aircraft measurements into a Global Observing System)

Predecessor (1993-2004):

MOZAIC (Measurement of Ozone and Water Vapour by Airbus In-Service Aircraft)
Regular vertical profiles: Aircraft

IAGOS: From MOZAIC to Sustainability

1993
MOZAIC I+II
Size & Weight
135 kg

2001
MOZAIC III
135 + 50 kg

2004
IAGOS
FP6 Design Study
100 kg

2005

2008

IAGOS-ERI
European Research Infrastructure
10-20 longrange aircraft, global coverage

Ambition & Scope
O$_3$ + H$_2$O

O$_3$ + H$_2$O + CO + NOy

O$_3$ + CO + NOy + NO$_2$ + H$_2$O + CO$_2$ + clouds + aerosol
IAGOS (Integration of routine Aircraft measurements into a Global Observing System)
Picarro CRDS system

SBIR (Small Business Innovation Research) project with Picarro & NOAA
- Modifications to ensure stability
- Size/weight reduction
- Repackaging & Certification
- First deployment in 2011, up to 7 A340 aircrafts

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tr>
<td>$CO_2$ Precision</td>
<td>&lt; 100 ppbv</td>
</tr>
<tr>
<td>$CH_4$ Precision</td>
<td>&lt; 1 ppbv</td>
</tr>
<tr>
<td>$H_2O$ Precision</td>
<td>&lt; 50 ppmv</td>
</tr>
<tr>
<td>Measurement Speed</td>
<td>&lt; 1 second</td>
</tr>
<tr>
<td>Drift (30 hours)</td>
<td>&lt; 150 ppbv</td>
</tr>
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</table>
Validation of FTIR column retrievals for CO₂ against CERES aircraft data

FTIR (NIR) vs. Aircraft + TM3 Model (above 4 km)

Precision < 0.5 ppm

[Regular vertical profiles: FTIR]

[MetAir Dimona (B. Neininger)]

[Bruker 120 M (J. Notholt, U. Bremen)]

[R. Macatangay, U. Bremen & MPI Jena]
Closing remarks

• Model-data-fusion:
  - Merging bottom-up and top-down is required, otherwise both are underconstrained at relevant scales

• High resolution information from intensive campaigns:
  - important for model validation

• Mesoscale modelling with WRF-VPRM:
  - VPRM captures NEE on relevant spatial and temporal scales
  - WRF-VPRM captures main mesoscale transport features

• Models aren’t perfect, and they will never be.
  - reduction and characterization of uncertainties is required
  - representation error: not necessarily random
  - mesoscale modeling required to bridge the gap to global models
  - aggregation error: specification of a priori uncertainty and covariances needed (may be solve for?)
Closing remarks II

• Transport: modified measurement strategy can help
  - PBL height: additional measurements needed near towers, assimilation into transport fields
  - Vertical mixing: regular vertical profiling
    ➔ IAGOS, FTIR, OCO, GOSAT

• To utilize long term & large scale information from mixing ratio observations, we first need to model (or parameterize) the short term & small scale with minimal bias
Thank you.